HYPERSPECTRAL REMOTE SENSING OF THE BRAZILIAN PANTANAL LAKES

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1. INTRODUCTION

Located in the center of South America, mostly in Brazil, the Pantanal is considered the largest complex of wetlands of the world (Alho et al., 1988; Tundisi, 1994). From the ecological, biological and economical points of view, thousands of small shallow fresh and salt water round lakes are responsible for the supply of water and food for human beings and animals and of salt for cattle. They have also a very important role as temporary or unique habitats for several native species of mammals, reptiles and aquatic birds (Brum and Souza, 1985; Pott et al., 1987; Campos, 1991).

The Pantanal is one of the least known regions of the planet. The difficulty to access many areas is one of the major factors responsible for the scarce scientific knowledge on the lakes. In the study of the lakes, remote sensing investigations are restricted to a very small number of published papers. For example, Abdon et al. (1998) reported the discrimination of aquatic plant covers especially in areas with *Salvinia auriculata* and *Scirpus cubensis* through the use of multispectral remote sensing (TM/Landsat 5 and HRV/SPOT images). However, to address the difficulty to distinguish areas occupied by different mixtures of aquatic plants, they suggested the use of data with better spatial and spectral resolution. In this sense, hyperspectral remote sensing introduces new perspectives for the study of the Pantanal lakes. The possibility of comparing pixel spectra with field spectra of water or aquatic plants, retrieving narrow absorption bands on a per-pixel basis, and of relating the spectral characteristics of the Pantanal lakes with physico-chemical databases is essential to understand the relationships between reflectance and water constituents.

In August 1995, at the peak of the regional dry season, the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) acquired images in the Brazilian Pantanal region in 224 bands (400-2500 nm) with 20 meters of spatial resolution. By inspection of these images, a subset of 12 lakes with distinct characteristics was selected for field investigation and spectral and physico-chemical data collection. The objective of this article is to discuss the spectral behavior of these lakes face to variations in water constituents.

2. METHODOLOGY

The location of the study area (approximately 10 x 20 km) is depicted in Figure 1. AVIRIS data were acquired in August 1995, at the peak of the regional dry season, from an altitude of 20 km. Images were obtained in 224 bands (10 nm in width) positioned in the 400-2500 nm interval, with a solar zenith angle of 34^{o} and a nominal spatial resolution of 20 m. AVIRIS radiance values were converted to surface reflectance data, that is, corrected for the scattering and absorption atmospheric effects, through the use of the Atmosphere Removal (ATREM) technique (Gao et al., 1993). After calculating the surface reflectance data, the Empirical Flat Field Optimal Reflectance Transformation (EFFORT) technique (Boardman, 1998) was applied over the images at selected spectral intervals to smooth noisy data resulting from the atmospheric correction procedure.

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Figure 1 - Spatial distribution of the Pantanal in Brazil and location of the study area.

The selection of the lakes for field inspection was based on the analysis of true color composites and of pixel spectra. The Bidirectional Reflectance Factor (BRF) at 39 sampling sites of seven fresh water and five salt water lakes were collected from a boat using a portable spectrometer (SPECTRON SE-590). The sensor collected data in the 400-900 nm range at spectral intervals of 3 nm and with 15^{o} FOV lens. A $BaSO_4$ plate of known reflectance was used as reference. Each one of the 39 collected spectra was the average of five continuous readings.

At each site, besides the reflectance data, the following in-situ measurements were performed: electrical conductivity, pH, total depth of the lake and Secchi disk transparency or Secchi depth. In laboratory, 33 water samples were submitted to chemical analysis. The methods used for determination of the water constituents were: calcium (Ca), total iron (Fe), magnesium (Mg), potassium (K) and sodium (Na) (atomic absorption spectrometric method); total phosphorous (P) (colorimetric and ascorbic acid method); total organic nitrogen (N) (Kjeldahl method); dissolved organic carbon (DOC) (colorimetric method); and total concentration of chlorophyll *a* plus phaeophytin (Chl) (spectrophotometric method). Details on these methods are described in Eaton et al. (1985). The total suspended solids (TSS) was determined by filtering samples onto 0.45 μm filters of known weight, drying them, and measuring the weight gain due to sediment concentration.

To characterize variations in depth of the main absorption bands present in pixel spectra, the continuum removal method (Clark and Roush, 1984) was applied to normalize the curves, to isolate the features, and to allow their comparison from a common baseline. Straight line segments connecting the edges (reflectance maxima) of the absorption band centered at 630 nm were chosen to define the continuum. The depth of the absorption band (D) was computed from the equation “$D = 1 – Rb/Rc$”, where Rb is the reflectance value at the center of the absorption band, and Rc is the reflectance of the continuum at the same wavelength as Rb.

3. RESULTS AND DISCUSSION

Figure 2 shows a true color composite (AVIRIS bands centered at 667 nm, 559 nm and 480 nm displayed in red, green and blue colors, respectively) and the location of the lakes selected for field inspection. Despite the non-existence of AVIRIS data for lake 7, which is located very close to the border of lake 6, its selection for investigation is due to its similarity in field with the bluish lake 3 indicated in Figure 2.

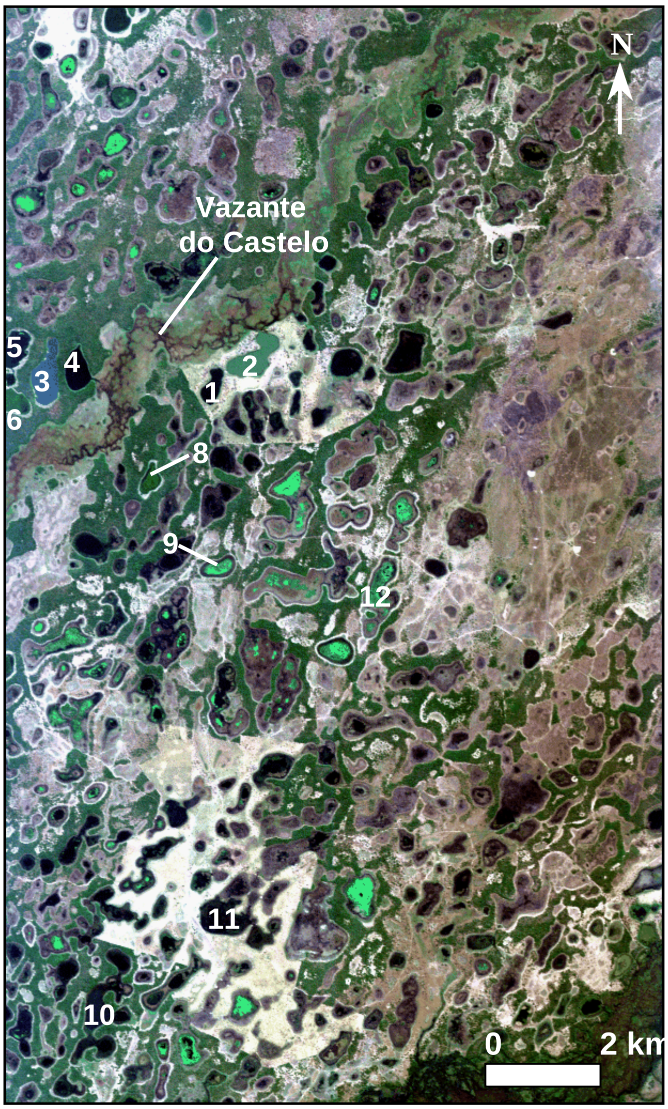

Figure 2 - True color composite of the study area with the AVIRIS bands centered at 667 nm, 559 nm and 480 nm depicted in red, green and blue colors, respectively. The location of the lakes selected for investigation (except lake 7) is indicated. The location of the "*Vazante do Castelo*", a temporary drainage channel, is also shown.

The fresh water lakes 1, 2 and 4, which display dark or light green colors in Figure 2, are characterized by the occurrence of small amounts of aquatic macrophytes (e.g., *Eichhornia azurea* and *Salvinia auriculata*) in their margins. On the other hand, the surface of the fresh water lakes 9 and 12 are dominated by a dense cover of floating vegetation, composed of *Nymphaea amazonum*, *Nymphaea lingulata* and *salvinia auriculata*. These aquatic plants are responsible for the green colors observed in the color composite of Figure 2. A lesser dense cover of aquatic plants, composed of *Eicchornia azurea*, *Oxycaryum cubense* and *Nymphaea amazonum,* are predominant in lakes 10 and 11.

The salt water lakes appear in greenish (lakes 5, 6 and 8) and bluish (lake 3) colors in the true color composite of Figure 2. However, the green color of lake 8 is the result of the strong background influence of the submerse rooted macroscopic algae *Chara rusbyana* that densely covers the bottom of this shallow lake.

Table 1 shows average and standard deviation values of the physico-chemical characteristics of the studied lakes. In general, when compared with the fresh water lakes, the salt water lakes, especially the more saline water bodies (lakes 3, 5 and 6), tend to present lower values of total depth and Secchi depth, and higher contents of DOC, TSS, Ca, Mg, Na and K. As illustrated in Table 1, the salt water lakes are composed of alkaline waters (pH > 9) with high values of electrical conductivity that may reach more than 3500 μS/cm in the more saline lakes.

Table 1 – Average and Standard Deviation (in Parentheses) Values of the Physico-Chemical Characteristics of the 12 Studied Fresh Water (F) and Salt Water (S) Lakes.

L	Chl μg/L	DOC mg/l	TSS mg/l	Secchi m	Depth m	pH	EC μS/cm	Ca mg/l	Fe_t mg/l	P_t mg/l	Mg mg/l	N_t mg/l	K mg/l	Na mg/l	N
1	724.6	0.13	3.07	0.35	0.97	8.99	97.1	1.07	0.63	0.12	0.63	120.3	8.60	2.37	3
(F)	(570.9)	(0.02)	(0.42)	(0.00)	(0.25)	(0.36)	(2.44)	(0.06)	(0.04)	(0.04)	(0.27)	(9.52)	(0.56)	(0.23)	
2	579.4	0.13	2.17	0.30	0.83	8.87	62.5	1.40	2.73	0.08	0.27	79.9	4.43	2.20	3
(F)	(429.5)	(0.02)	(0.19)	(0.00)	(0.21)	(0.60)	(0.15)	(0.61)	(0.31)	(0.02)	(0.27)	(40.0)	(0.46)	(0.44)	
4	68.0	0.11	16.41	0.40	0.87	6.68	72.2	1.97	3.85	0.65	0.29	121.6	4.02	1.75	4
(F)	(25.9)	(0.01)	(2.30)	(0.00)	(0.09)	(0.17)	(1.60)	(0.09)	(0.93)	(0.62)	(0.14)	(44.0)	(0.40)	(0.90)	
9	62.4	0.05	5.25	0.80	0.88	6.37	105.0	4.10	2.00	0.01	0.25	22.2	3.20	9.20	2
(B)	(35.7)	(0.00)	(2.33)	(0.00)	(0.04)	(0.04)	(38.0)	(0.14)	(0.00)	(0.00)	(0.08)	(7.92)	(0.28)	1.13	
10	468.8	0.02	0.80	1.32	1.57	6.11	37.5	1.75	0.80	0.01	0.30	12.5	4.70	2.27	4
(F)	(395.5)	(0.00)	(0.58)	(0.09)	(0.15)	(0.26)	(2.01)	(0.01)	(0.40)	(0.00)	(0.09)	(5.30)	(0.22)	(0.29)	
11	62.0	0.03	1.10	1.10	1.10	6.29	34.9	1.80	1.60	0.01	0.14	9.80	5.10	2.00	1
(F)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
12	183.7	0.06	3.40	0.70	0.70	6.14	105.2	6.30	2.75	0.01	0.61	16.75	6.05	7.95	2
(F)	(96.5)	(0.01)	(4.24)	(0.00)	(0.00)	(0.11)	(2.90)	(0.28)	(1.06)	(0.00)	(0.19)	(8.84)	(6.86)	(0.07)	
3	95.6	1.05	39.16	0.07	0.42	9.33	4907	13.66	28.9	4.55	9.11	66.3	188.5	394.4	7
(S)	(73.9)	(0.04)	(10.9)	(0.00)	(0.07)	(0.03)	(55.0)	(1.35)	(4.42)	(0.45)	(5.78)	(23.7)	(26.9)	(56.4)	
5	538.3	0.62	200.6	0.08	0.45	10.19	3882	9.08	1.22	0.02	0.87	66.3	117.2	255.5	5
(S)	324.9	(0.01)	(51.4)	(0.00)	(0.28)	(0.11)	(25.9)	(1.28)	(1.67)	(0.03)	(0.91)	(64.9)	(64.0)	(142)	
6	778.9	0.43	220.3	0.09	0.45	10.44	4293	8.73	0.38	0.01	1.47	42.2	165	384.4	3
(S)	(34.3)	(0.02)	(9.81)	(0.00)	(0.05)	(0.07)	(130)	(2.31)	(0.16)	(0.00)	(0.55)	(5.91)	44.2	(123)	
7	267.3	2.07	42.70	0.06	1.10	9.07	1530	9.40	105.3	0.39	5.87	17.5	46.1	145.6	2
(S)	(-)	(0.05)	(37.2)	(0.00)	(0.21)	(0.17)	(14.1)	(0.00)	(0.00)	(0.11)	(0.64)	(1.13)	(0.14)	(7.07)	
8	103.6	0.06	5.88	0.30	0.30	9.91	1590	5.33	0.35	0.01	0.26	12.7	73.6	88.2	3
(S)	(30.5)	(0.01)	(5.07)	(0.00)	(0.00)	(0.47)	(70.0)	(1.15)	(0.31)	(0.00)	(0.32)	(1.75)	(7.52)	(7.91)	

Figure 3 exhibits water reflectance spectra representative of the saline lakes (Fig. 3a), of the fresh water lakes affected by the floods of the *Vazante do Castelo* (Fig. 3b), and of the fresh water lakes covered by aquatic plants (Fig. 3c). In Figure 3a, the greenish salt water lakes 5 and 6 show spectra with well-defined chlorophyll absorption bands at 450 nm and 667 nm, a green reflectance peak at 556 nm, a narrow absorption band at 630 nm due to phycocyanin, and a broad spectral feature around 750 nm due to water absorption. The phycocyanin feature is not present in the spectrum of lake 8, which is a mixed spectral response of relatively transparent water and algae (*Chara rusbyana*). The featureless spectra of lakes 3 and 7 and their resulting blue colors in the images are produced by an increase in the DOC concentration, which masks absorption bands due to other constituents, and by a decrease in the content of chlorophyll (Table 1). In Figure 3b, the larger concentration of TSS in lake 4 (Table 1), in relation to lakes 1 and 2, produces an increase in reflectance in the red interval.

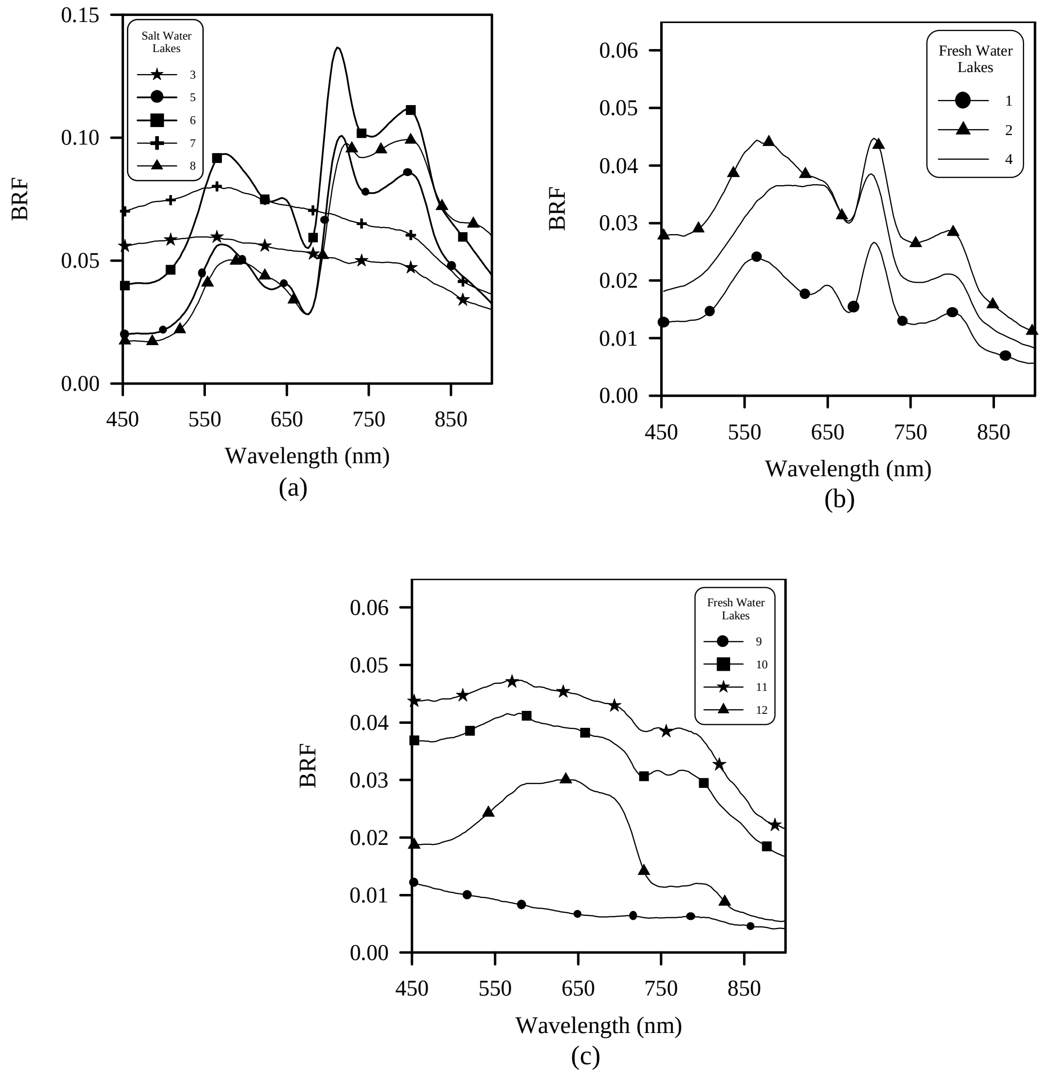

Figure 3 - Field bidirectional reflectance factor (BRF) values for the (a) salt water lakes, (b) fresh water lakes without dense aquatic plant covers at the *Vazante do Castelo* drainage, and (c) for the fresh water lakes with extensive aquatic plant covers.

The comparison between field (Spectron) and airborne (AVIRIS) data reveals interesting aspects. The capability of AVIRIS in retrieving the narrow 630 nm absorption band is shown in Figure 4, which displays variations in the depth of the 630 nm absorption band derived from the continuum removal method. The characterization of this feature is important because it can be useful in the identification of broad algae group of species (Jupp et al., 1994). As indicated in Figure 4, the deepest 630 nm absorption band occurs in pixel spectra of the fresh water lakes 1 and 2 and of the greenish salt water lakes 5 and 6, which is consistent with the results of Figure 3.

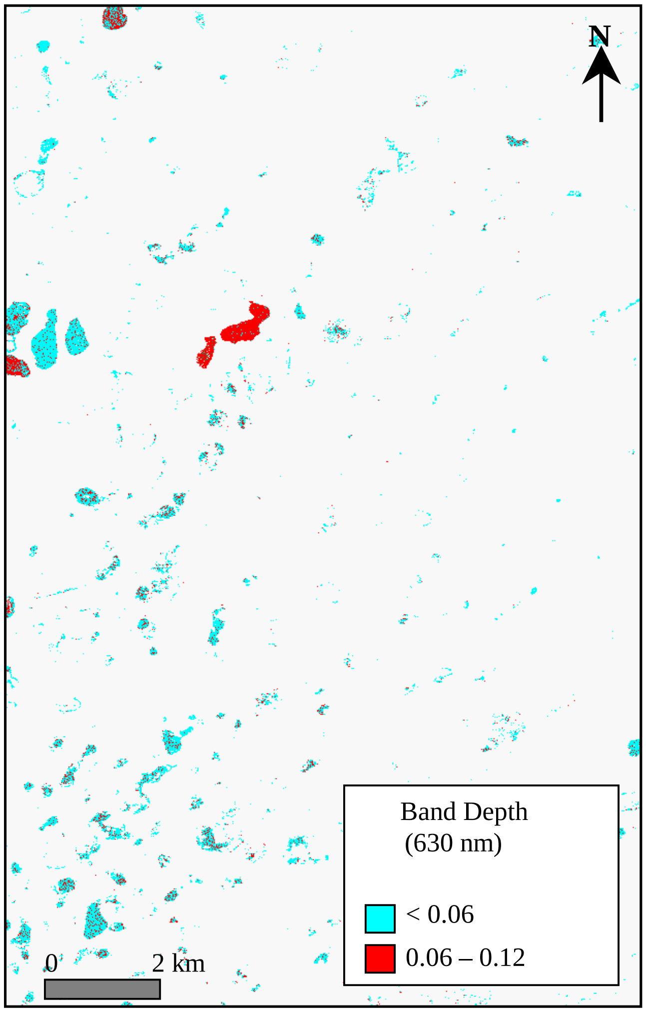

Figure 4 - Variations in the depth of the 630 nm absorption band for lakes without dense covers of aquatic plants.

On the other hand, the strong spectral influence of the macrophytes on the lakes 9 to 12 is illustrated in Figure 5 that displays AVIRIS pixel spectra. Lakes 9 and 12 are densely covered by *Nymphaea amazonum*, *Nymphaea lingulata* and *Salvinia auriculata* that completely obliterate the spectral response of the water. The pixel spectra of these lakes exhibits a well-defined green reflectance peak. Lakes 10 and 11 are dominated by *Eicchornia azurea*, *Oxycaryum cubense* and *Nymphaea amazonum* that show a different spectral pattern. As a result, spectra of Figure 5 are very different from those displayed in Figure 3c that shows field water reflectance spectra of lakes 9 to 12.

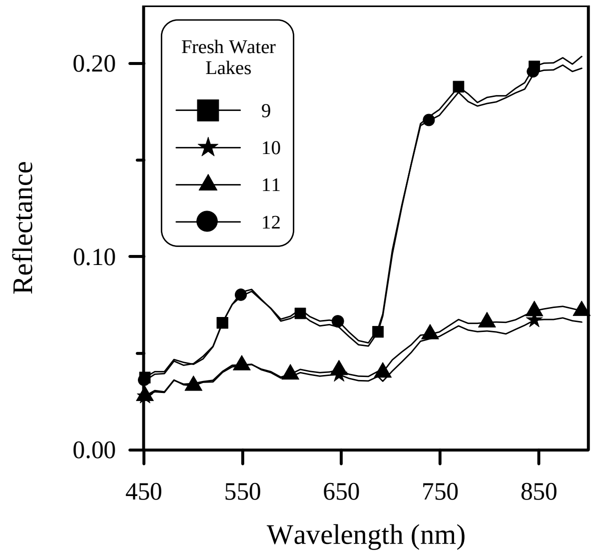

Figure 5 – AVIRIS pixel spectra representative of lakes 9 to 12 with covers of aquatic plants.

4. CONCLUSIONS

The transition from the fresh water lakes to the salt water lakes in the study area is characterized by lower values of total depth and Secchi depth, greater concentrations of DOC, TSS, Ca, Mg, Na and K, and higher values of pH and electrical conductivity. The saline lakes presented a higher overall reflectance than the fresh water lakes. In comparison with the greenish salines, the bluish salt water lakes show an increase in the DOC concentration, which masks absorption bands due to other constituents, and a decrease in the content of chlorophyll. In some fresh water lakes, the presence of dense covers of aquatic plants restricts the spectral response of water to a small number of pixels.

Hyperspectral data are very important in the selection of the Pantanal lakes with distinct spectral characteristics for field sampling, which facilitates the subsequent construction of empirical relationships or more elaborated methods for the remote estimate of water constituents. They allow a better characterization of the variations in reflectance and in related absorption band parameters due to changes in water constituents. Major spectral features present in field spectra, such as the narrow 630 nm absorption band, were also observed in AVIRIS spectra of some lakes and mapped on a per-pixel basis. Hyperspectral sensors can provide also an important contribution in the characterization of aquatic plant covers in the Pantanal lakes because of the well-defined spectral signatures of some species.

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